MINISTRY OF DEFENCE

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ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT

REPORT 2/84

Some Historical Aspects of the Development of Shaped Charges

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Halstead

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R F Eather, BSc
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Summary

A short account is given of shaped charge development, starting in Norway in the 18th century, noting the first patent applications and then concentrating upon UK developments during World War II and the following years.

Approved for issue:

R Griffiths

CONTENTS

1 INTRODUCTION

The forerunner of this report was an invited paper on historical aspects of shaped charge activities as seen in the UK, which was given at a conference hosted by MBB Schrobenhausen, West Germany, to celebrate both its own silver jubilee and the centenary of shaped charge work in that country.

While the paper was being prepared, it became apparent that there is a very large literature on the early shaped charge work which is still relevant today, but which has remained largely undisturbed for many years. This report is intended as a brief survey, providing the interested reader with key document references which would then act as starting points for further researches. It does not purport to give a complete bibliography.

A certain apology may be needed in that the writers may not have stressed some aspect of this subject which interests a particular reader: this is excused partly by the very involved nature of the subject and partly by the limited time available for a perusal of the available literature.

2 EARLY HISTORY

The cavity effect in explosives has been the subject of intermittent investigations for well over 150 years and has been discovered by many people during that time. The earliest available reference (Ref 1) is to the work of Baader, a Norwegian mining engineer, who towards the end of the 18th century advocated leaving a conical or mushroom-shaped air space under the forward end of a blasting charge. This space increased the explosive effect and at the same time saved a considerable amount of explosive. Hausmann (Ref 2) took the idea from Norway to Germany early in the 19th century, but it appears not to have flourished in the Harz mines according to Combes (Ref 3). In 1874 Davey and Watson took out a British Patent (No2641) in which they claimed as a new invention, "the use of a cylindrical charge with a central hole below and in the middle".

In 1883 Max von Foerster in Germany (Ref 4) discovered a similar effect, as did the better known Munroe in Washington. Munroe's work, first mentioned in an article published in 1885 (Ref 5), showed that any pattern forming an indentation in the base of an explosive charge was reproduced as an indentation in an underlying metal plate when the charge was detonated (Fig 1). From this he extended his investigations to establish the effect of different sized holes in wet guncotton cylinders. The deeper and wider the holes in the guncotton, the deeper and wider the holes bored in the iron plate. When there was a hole completely through the guncotton cylinder (and at least half of the weight of explosive had been removed), the iron plate was completely perforated when the charge was detonated.

In 1911 M Neumann mentioned (Ref 6) the discovery that a hollow in the side of an explosive body turned towards the object to be attacked increased the effect from 3 to 4 times. In 1914 E Neumann published (Ref 7) the results of investigations into the effect of hollowing out explosive charges, which he claimed to be an entirely new method developed by his company Westfalisch-Anhaltische Sprengstoffe A-G. This method had been the subject of a German Patent No 249,630 by the company in 1910, and of a British Patent No 28,030 in December 1911. There is no evidence from this time that either Munroe or the Neumanns discovered the lined cavity effect. British researchers started work on shaped charges in more detail when this patent action was taken. Ordnance Board records show (Ref 8) that in 1913 the Navy studied shaped charges for a torpedo warhead, but the technology was not advanced significantly, although the claims made in the patents were confirmed. The Army took a more sceptical view (Ref 9) and considered that the use of hollow charges in projectiles was impractical because it would be difficult to prevent the forward set of the charge on impact. There was also the difficulty of locating the fuze, which from the nature of the charge had to be at the base, and a base fuze was not an acceptable feature at the time. The enhanced effect was explained as being due to a more complete detonation of the explosive and it was considered that a similar effect could be obtained by using a more powerful detonator.

Interest in shaped charges then declined and it was not until the late 1930s that serious efforts were made to exploit them for military purposes, in particular shaped charges with lined cavities. Payman and Woodhead (Ref 10) working at the Safety in Mines Research Station, Buxton with unlined charges showed the importance of solid particles carried in the detonation products in producing and prolonging the intense 'end effects'. Using spark photography they discovered that the mean axial speed of the wave sent out into the atmosphere from a fully wrapped cartridge was 2010m/s, while that from a cartridge with a conical indentation was 2740m/s. It subsequently became known that the 'end effects' were even more remarkable when the hollow was lined with material. Eichelberger (Ref 11) credits R W Wood of Johns Hopkins University, USA with the recognition in 1936 of the usefulness of metallic liners, but it is quite likely that it was discovered earlier by workers at Woolwich Arsenal and in Germany. W M Evans certainly worked in the field in the 30s, as did Thomanek in Germany.

3 THE MOHAUPT DEMONSTRATION

In 1938 Dr Mohaupt, a Swiss inventor, approached the British Military Attaché in Zurich and told him that he had discovered a new and powerful explosive. He proposed that the British should purchase an option on his invention for a few months for £10,000.

In January 1939 two representatives from Woolwich Arsenal witnessed a demonstration by Dr Mohaupt of projectiles being fired against a thick steel plate. The projectiles exploded on contact with the plate leaving a small jagged hole right through the armour. Mohaupt went to some lengths to conceal how he had achieved this; he even added dye to the explosive to mislead the observers.

The Woolwich scientists concluded that what they had seen was due to a hollow charge effect and not to a new explosive. They had been able to produce in static trials results very similar to those of Mohaupt. He was informed that the British were fully aware of the hollow charge effect and had improved on the basic idea. It is not clear from the evidence whether the British appreciated that Mohaupt was using a lined cavity. Neither is it clear whether the British admitted to using lined cavities at Woolwich. Understandably the British decided that the payment of a large sum of money for the disclosure of the details of Mohaupt's new explosive was hardly justified (Ref 12). In 1939 Messrs Mohaupt, Mohaupt and Kauders applied for a French Patent (Application No467) for an "improved explosive projectile" which appears to have been similar in design to that submitted to the British Government. Mohaupt went on to participate in early developments of the lined cavity effect in America in the early part of World War II.

4 APPLICATION TO MUNITIONS

As a result of the Mohaupt demonstration the British reconsidered whether the shaped charge effect could be introduced into Service munitions, in particular using plastic explosive which was very attractive for demolitions and other applications because it could be formed easily into various shapes. The early studies concentrated on a shaped charge grenade that could be fired from the standard grenade discharger cup fitted to the Short Magazine Lee Enfield rifle (Figs 2 and 3). Grenades fired statically penetrated 52mm of armour, while the corresponding dynamic penetration was 44mm. This is equivalent to 1.6 and 1.3 charge diameters penetration respectively. The range of the weapon was only 100 yards; nevertheless, it was a valuable anti-armour weapon particularly in last ditch situations. After about a year's development it was introduced into British Service in November 1940 as the No 68 grenade. Thus the British were equipped with the world's first hollow charge, anti-tank rifle grenade. In fact we believe it was the first hollow charge, anti-tank projectile of any kind.

In 1940 and 1941 armours thicker than 44mm were often encountered and the British anti-tank rifles were inadequate for their intended task. The grenade principle of using a discharger cup on a rifle made for too light a projectile and too short a range. Several designers bent their minds to the task and two prototype anti-tank devices appeared in 1941, both very similar in appearance and principle. One was designed by a man called Watts, the other by Jeffries. The launchers were tubes of thin sheet steel containing the firing spring and trigger mechanism. At the front was a trough to hold the bomb and the spigot projected down the middle of the trough. At the other end of the tube was a shoulder pad. Simple aperture sights were fitted. The bombs had a hollow tail boom with a small cartridge at the front end. The hollow charge warhead was larger in the Jeffries version.

On firing, the spigot passed up the tail boom and fired the cartridge. This launched the bomb which flew off the spigot on its way to the target. Meanwhile the force of the explosion moved the spigot back against its spring and recocked it. The moment the first bomb had left, another could be slipped into the trough and shooting continued. The production version was a meld of the Watts and Jeffries designs. There were several advantages to the system; it did not rely on a precision barrel, there was little muzzle blast and it could accommodate a fair sized warhead. With little muzzle flash and no back-blast it was perfectly safe to fire in confined spaces. These advantages have not been regained with modern weapons. The Watts/Jeffries weapon was given the pompous name of the Projector Infantry Anti-Tank, but it was known throughout the world as the PIAT (Fig 4).

Although the range of the weapon was short, the shaped charge bomb was capable of penetrating any tank armour existing at that time, but there was a spread on performance, with an average of 115mm of armour.

Bearing in mind that in 1940 there was little, if any, real theoretical understanding of the complex process of shaped charge collapse, the No 68 grenade and the PIAT were remarkably successful British developments.

5 RESEARCH 1941-45

5.1 Overview

Extensive experimental and theoretical research programmes proceeded in the UK during these years which led to a considerable increase in our knowledge of the complex mechanism of jet formation and jet/target interaction. Many people made important contributions to this new technology, but among the more well known personalities were:

Evans and Ubbelohde	Jet experiments
Taylor and Tuck	Hydrodynamic theory of jet formation

Hill, Mott and Pack	Theory of target penetration
Soper	Factors affecting performance

By the end of 1942 (Ref 13) it had been shown in Woolwich and South Wales that the shaped charge effect was not the result of simply focussing the energy of the explosive, rather it was a highly complicated process involving the type, shape and size of the explosive charge, the material and thickness of the liner in the hollow, the distance between the charge and the target and the medium through which the jet passed before reaching the target.

5.2 Jet Experiments

Evans and Ubbelohde (Ref 14) in their early work derived the mechanism of jet structure and formation by observing the damage produced by jets in massive steel targets which were located at different distances from the base of the hollow charge. They showed photographically that when unlined hollow charges were detonated, a thin pencil-like flame was projected along the axis of the hollow. The velocity of the flame near the charge was high but it decayed rapidly in the air. This explained why the early proposals to exploit shaped charge effects from unlined hollows required the explosive to be practically in contact with the target.

When the hollow was lined with a thin layer of metal, the volume of the crater in the target increased dramatically. The crater depth reached a maximum at many charge diameters from the base of the charge. This suggested that when the explosive detonated the metal lining formed some kind of projectile which persisted in space after the products of the explosion had dissipated. Initially it was not clear whether it was acting like a tongue of hot dense gas, or in the form of solid or liquid particles moving with high velocity.

The vaporisation characteristics of the projectiles were therefore studied by firing a series of charges with metal linings with increasing boiling points. Both shallow and deep hollows were used. With shallow hollows (spherical caps) a broad distinction could be drawn between metals such as steel, which gave wide diameter jets but with little penetrative power, and metals of much lower melting point and boiling point such as cadmium, which gave fine pencil-like jets of high penetrative power. In retrospect, it was ductility rather than melting or boiling point which was the determinant of performance.

When deep hollows were used, cones of angle 80° or less, the difference in penetrative power of jets from the different metals was less marked.

By a careful examination of the signatures of jets in the target it was established that most jets changed their shape as they travelled through space, probably because of velocity gradients in various parts of the jet. If the axis along which the jet would form was obstructed within the hollow, jet formation from the deep conical linings was largely prevented. This effect of an obstruction was much less marked with hemispherical and shallow holes, which indicated different mechanisms of formation for conical and spherical linings. The major process of collapse of the lining appeared to be complete within a distance of 1 to 2 charge diameters, depending on the shape of the hollow and the thickness and type of metal lining. Much later of course these deductions were confirmed with flash radiography.

Much was learnt about the various facets of jet formation and jet structure by recovering the projectile after travel in free air, in such a way as to minimise the damage on recovery. Jets were fired into broken ice, water, water soluble salts and solid carbon dioxide. These experiments showed that the material recovered from conical metal linings consisted of a plug of metal, which accounted for a considerable proportion of the total mass of the liner (the proportion depending upon the liner thickness), and a quantity of smaller fragments and finely powdered material. This work was subsequently published in the open literature (Refs 15 & 16).

During 1943 Kolsky, Shearman and Snow (Ref 17) at ICI Ltd in England were studying jet formation and concluded from their experiments that the liner accelerates rapidly and is forced in towards its base. The metal from the apex region was crushed together with such force that it flowed and a fine jet was extruded out along the axis. Pushing the apex of the cone outwards caused the cone walls to bend back and form a flange. The turning back of the cone walls was verified by using bimetal liners. When a lining had steel on the inside (the face away from the explosive) and copper on the outside, the plug also was steel on the inside and copper on the outside, but the jet fragments had the metals reversed. The jet was of steel and the penetration characteristics were those of steel. If the bimetal liner was reversed, the penetration characteristics were those of copper. Figure 5, which is a modern day set of flash radiographs of a shaped charge collapsing, is remarkably in keeping with the early theory.

In 1944 Kolsky wrote a companion paper concerning the collapse of hemispherical liners (Ref 18).

5.3 Effect of Charge Characteristics on Jet Formation

Since the energy of the jet is derived from the explosive, Evans and Ubbelohde (Ref 19) expected that, by analogy with other explosive effects, more powerful explosives would enhance the effectiveness of shaped charges. Systematic investigations with a range of explosives confirmed this hypothesis.

It was also shown (Ref 20) that good contact between the explosive filling and the metal liner was essential for efficient jet formation. Poor contact led to the formation of asymmetric jets which were poor penetrators.

Increased confinement was expected to result in improved performance provided it led to increased gas pressure during the collapse of the liner and the formation of the jet. Evans and Ubbelohde (Ref 21) implied that the length of the jet remained substantially unaffected by increased confinement, but the total kinetic energy increased up to a limit.

Poole at Woolwich suggested (Ref 22) that the shape of the detonation wave could be modified with advantage by using a core of explosive with a lower detonation velocity, so that there was a more nearly normal impact of the detonation wave over the walls of the liner.

5.4 Theories of Jet Formation

The mechanism of jet formation was a source of great controversy. Three major theories were put forward:

Kistiakowsky's Intersecting Shock Waves

Taylor in the UK and Birkoff in the US - Hydrodynamic Squirt Theory

The Du Pont Company in the US - Spalling Theory

Kistiakowsky's Shock Wave Theory (Ref 23) was based on the fact that when two plane shock waves intersect at an angle greater than 80°, before the waves diverge, an intense plane shock results acting perpendicularly to the bisector of the angle. This could account for the observed enhanced velocity of the jet, and the velocity gradient could be explained by the reduction of the detonation pressure in the region of the base of the liner where there was less explosive. The theory was not entirely satisfactory, and it failed to explain the separation of the liner material into a jet and a plug.

Professor G I Taylor wrote his first paper (Ref 24) in March 1943. In fact he prepared a mathematical formulation of certain ideas put forward by James Tuck (Ref 25) some weeks previously. Tuck, working in the Ministry of Supply, had suggested that the high jet velocity was simply due to hydrodynamic effects and could be explained by regarding the liner of the charge as a fluid conical shell which is given a velocity normal to the generators of the cone. This theory enabled Tuck to explain some of the simpler jet phenomena and he made a number of deductions and speculations:

a. It seemed likely that explosive located in the rear axial portion of the charge was not being used to advantage, and by redistributing it towards the periphery of the liner some improvement in performance might be obtained.

b. Composite Linings It followed from the theory that with axial initiation the base of the liner was the last part to arrive at the target. By using an appropriate material to make up this part of the liner it should be possible to inject the material through the hole made by earlier stages of the jet.

c. Multiple Charge In order to obtain increased performance from charges of restricted diameter, it was suggested that a number of successive co-axial charges should be used, detonated from the rear so that the plugs did not obstruct the jets. Experiments confirmed that a useful measure of increased performance could be obtained in this way.

Tuck's report contains what are believed to be the first spark photographs of Munroe jets. They were taken by staff working at the Road Research Laboratory.

Professor Taylor described Tuck's work mathematically and accounted for the thin jet and the thick plug; the former had a higher velocity than the latter. More importantly he showed how a forward velocity of the thin jet could be greater than the collapse velocity of the cone walls. His theory did not however account for the formation of secondary fragments and the bending back of the liner. The essential parts of the theory were supported qualitatively by radiographs and other experimental evidence. After the war Taylor collaborated with Birkhoff in writing what has become a standard work on this topic (Ref 26).

The Dupont theory on spalling assumed that the inner part of the cone wall was ripped off by a Hopkinson Bar effect, and the spalls then travelled towards the axis where they collided to form the jet. The remaining part of the cone collapsed to form the plug. However, the theory did not account for the focussing of the particles and the enhancement of velocity in the jet, and it soon lapsed.

5.5 Experiments on Target Penetration

During 1942 and 1943 studies were concentrated on elucidating the mechanism of penetration of jets into metals. At one stage it was thought the mechanism was mainly one of erosion because of the high temperatures which could be generated when the jet impacted on the target. Subsequently, Evans and Ubbelohde (Ref 27) discovered that when a high energy jet hit a metal target such as steel, the very high pressures set up in the steel were so much greater than its yield strength that the steel behaved like a fluid.

Metallurgical examination of the target after penetration showed that the high rate of motion had caused the material to be displaced almost at right angles to the path of the jet; there was very little displacement in the direction of motion of the jet.

Extensive experiments were carried out with a number of different liner materials to establish their effect on penetration and crater formation. The results of these experiments led to a sub-division of metallic linings - fluid and fragment. This was done to differentiate between the deduced penetration laws and was not intended to convey that a fluid jet was literally what its name implied. Rather it consisted of much finer particles than a fragmenting jet and it penetrated a target as if it were a fluid.

These penetration investigations were not limited to attacking massive steel targets; spaced plates even at that early time received some attention too. Ubbelohde (Ref 28) discovered that as the distance between successive plates increased, there was a tendency towards an upper limit of loss of penetrating power per air gap, and he compared the thickness of steel penetrated under these conditions with the penetration which would be achieved in a massive target. This loss in penetration against spaced plates was considered to be due to the dispersion of fragments punched from the plates by the jet, which were thus lost and could not contribute to the penetration of succeeding plates. He came to the important conclusion that to protect against persistent jets, the number of discontinuities in a given weight of steel should be made as large as possible, but the space between the plates need not be more than about one charge diameter.

Little work was done at the time on the effect of spinning charges; this came later (Ref 29). Experiments with Service munitions such as those for the 25pdr field gun and the 3.7 inch howitzer did show that when a charge was rotated the resulting craters in the armour were shallower and wider. The systematic investigation of this effect was not possible until about 1950.

5.6 Target Penetration Theory

In January 1944 Hill, Mott and Pack (Ref 30) published their work describing their attempt to obtain penetration laws theoretically. They developed the Evans and Ubbelohde view that the pressure exerted by most jets greatly exceeded the yield strength of the target material. So far as this approximation held, the penetration could be treated mathematically by hydrodynamic laws governing the penetration of a liquid as a result of the pressure exerted by the jet. They deduced the following from their theory:

a. The depth of penetration by the same jet in different targets should be inversely proportional to the square root of the density of the target material, but should not depend on target strength.

b. The depth of penetration is independent of jet velocity.

c. In order to obtain jets of increased penetrating power it is necessary to increase jet length or density. Since the jet length normally increased with stand-off this explained improved penetration with increasing stand-off.

During 1945 Pack and Evans modified the Hill-Mott-Pack theory to take account of velocity distribution in the jet and the effect of target strength (Ref 31). The final form of the Pack-Evans penetration analysis was completed in 1946 (Ref 32).

5.7 Status 1945

The most intriguing aspect of the hollow charge effect was the high speed jet in its composition and physical and ballistic properties. Jet formation was fundamentally understood on the Taylor-Birkhoff lines and the jet penetration theory of Hill et al was basically sound. However, the derivation of quantitative results from these steady state theories was very much in its infancy. There was still considerable uncertainty about the particulate nature of the jet; collection techniques had shown the presence of a very large number of small particles and their density seemed to be uniformly distributed along the jet. However, the mere act of collection could have led to a change in size distribution.

A wide variety of liner materials and explosives had been characterised experimentally. The No 68 anti-tank grenade had been superseded by the No 85 grenade (Fig 6), and the dynamic penetration had increased to 1.5 charge diameters. Applying the hollow charge principle to gun-fired projectiles increased the number of factors affecting performance, in particular fuzing and stabilisation. Stabilisation introduced the problem of the rotated charge and one of the major challenges of the time was to overcome the serious degradation in performance that was brought about by spinning. This will not be dealt with here except to note that the British anti-tank HESH shell precluded the need for a gun-fired HEAT shell.

6 POST 1945

Work on rifle grenades ceased; they were not robust enough for defeating tanks and only sporadic work was done on gun-fired ammunition. The principal areas of interest were the factors which might contribute to the observed variation in performance, refinements in shape and material of the liner and detonation wave shaping.

It was noted that the fabrication and filling of charges required high precision if maximum and reproducible results were to be obtained. Misalignment of the cavity axis with the axis of the explosive charge decreased performance. Uneven thickness of the metal liner, formation of a non-uniform layer of explosive at the base of the cavity and voids or low density regions in the explosive were all found to have adverse effects on performance (Ref 33). An extensive bibliography and review was prepared by Fricker and Tupper in 1951 (Ref 34).

Later, in 1952 Tupper (Ref 35) extended the Taylor-Birkhoff theory to asymmetric collapse; this important paper is not well known but it gives the theoretical justification for the need for symmetry in the collapse process.

The success of British APDS ammunition and the invention of HESH meant that there was no priority requirement for hollow charges until the advent of guided weapons when studies expanded again, leading to the efficient systems we know today. Shaped charges developed in the UK in the last twenty years, include the warheads for the following weapons (Figs 7-12):

Weapon	Penetration Performance* (Cone Diameters)
Vigilant	3.9
Swingfire Mkl	
BL755	3.7
Blowpipe	
LAW 80	~7
JP233	~6**
Future	10 ?

* Into armour at built in stand-off of weapon
** Has aluminium cone and penetration measured into concrete/soil.

So from the late thirties with the No 68 grenade, we have improved performance from 1.3 cone diameters penetration to around seven cone diameters with LAW 80. The latter exploits a copper liner with controlled grain size and texture, a nucleated explosive to guarantee homogeneity in the region of the liner, and a wave shaper to ensure a more nearly normal impact of the detonation wave on the liner wall. A remarkably uniform jet is produced from this charge (Fig 13). Currently high density materials are under careful examination and there is the potential of increasing penetration to 10 cone diameters.

7 ACKNOWLEDGEMENT

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FIG 1

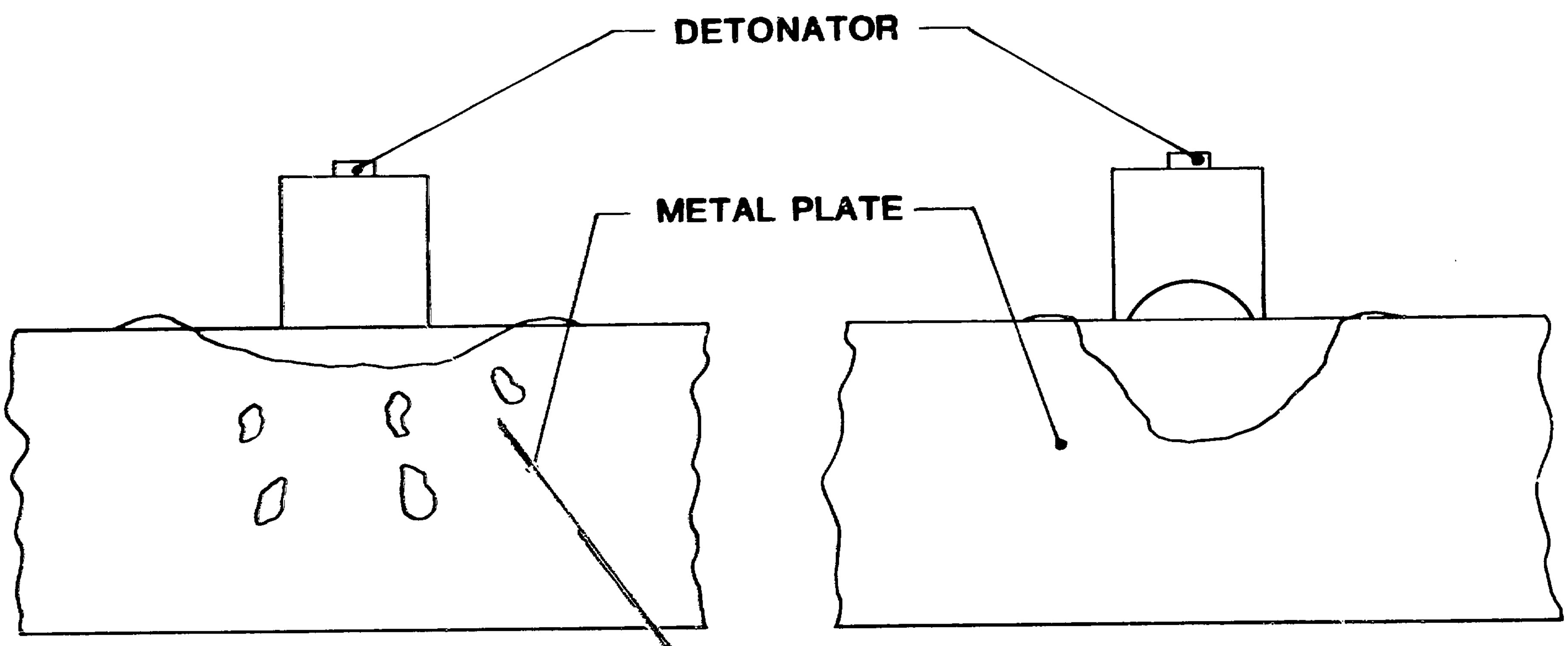

FIG 1 EFFECT ON METAL TARGET
OF A SOLID CHARGE AND AN UNLINED SHAPED CHARGE

UNLIMITED

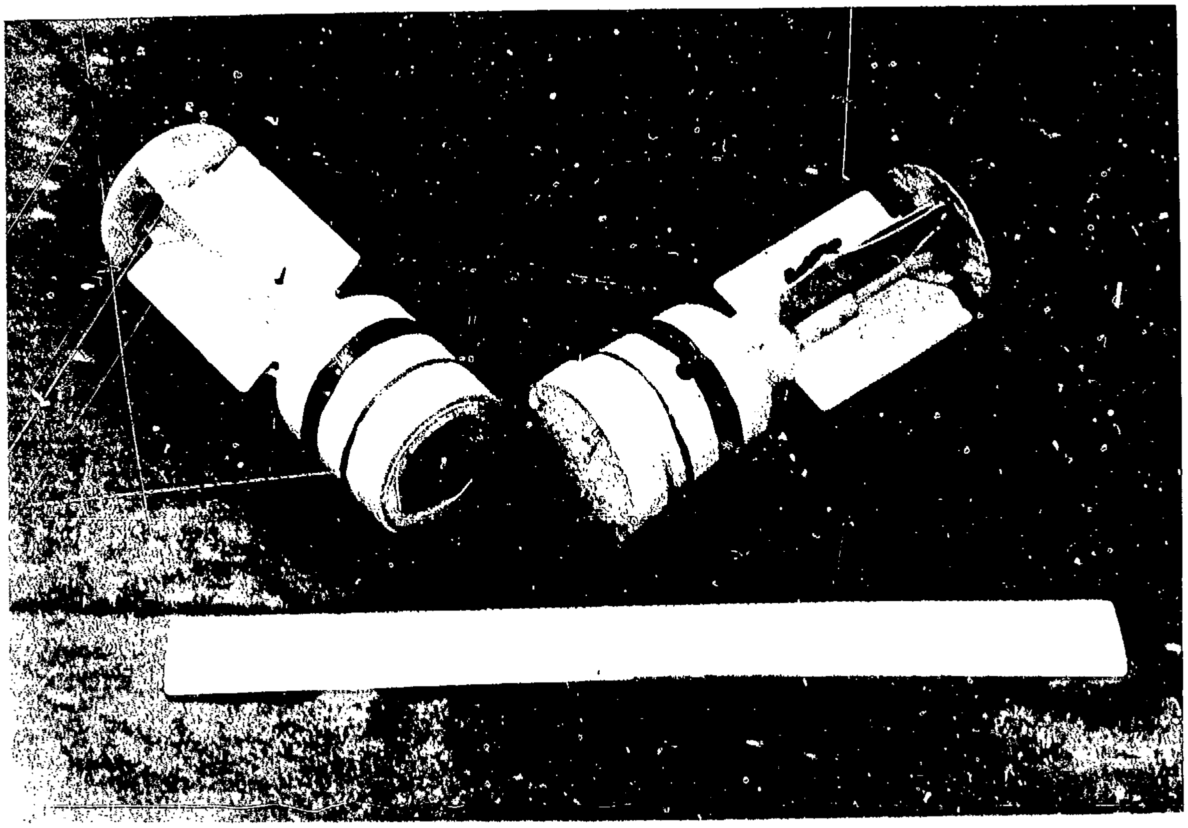

FIG.2 GRENADE NO. 68
EXTERNAL VIEW

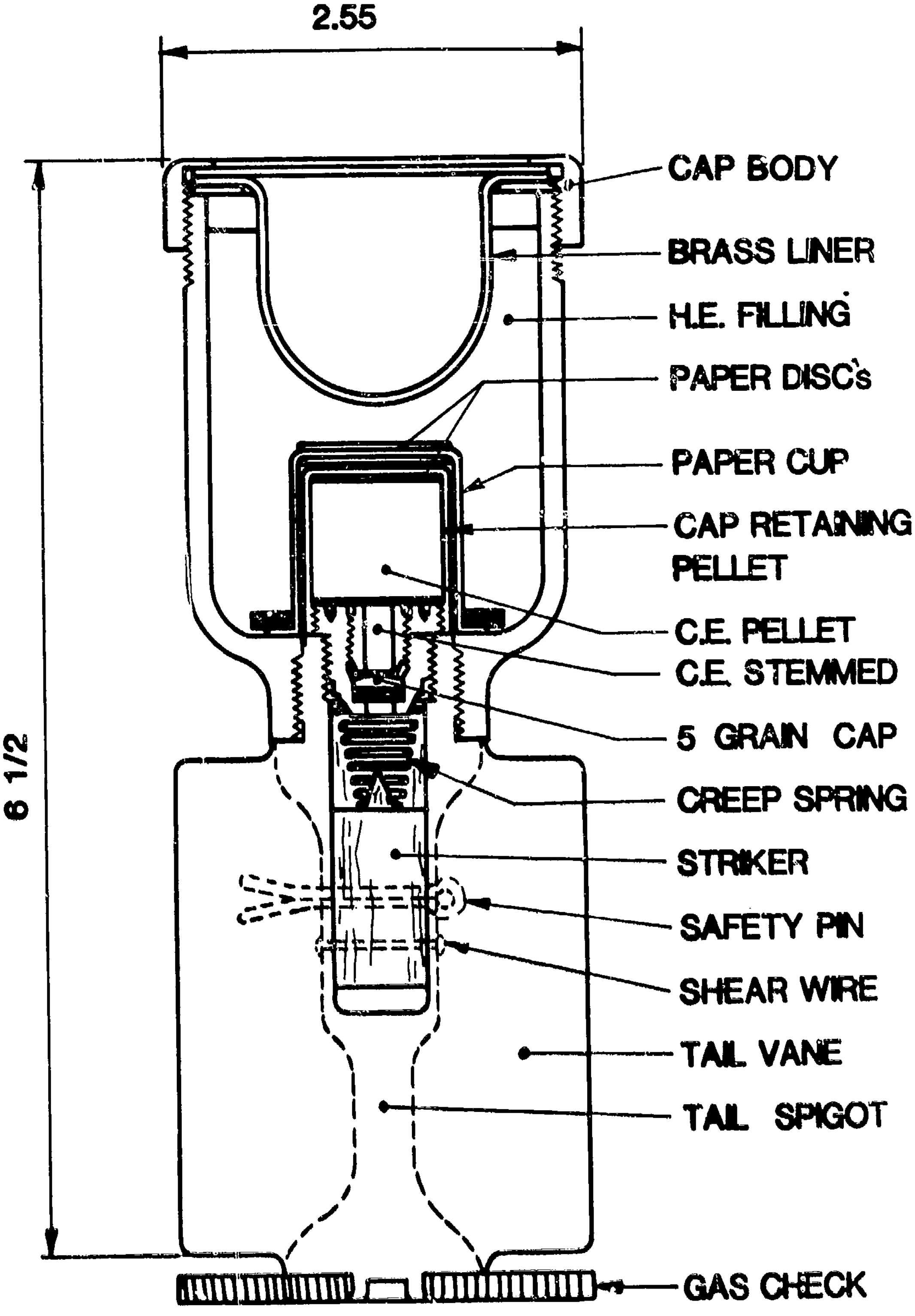

FIG 3 GRENADE NO. 68
INTERNAL SCHEMATIC

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FIG.4 PROJECTOR INFANTRY ANTI-TANK (P.I.A.T.)

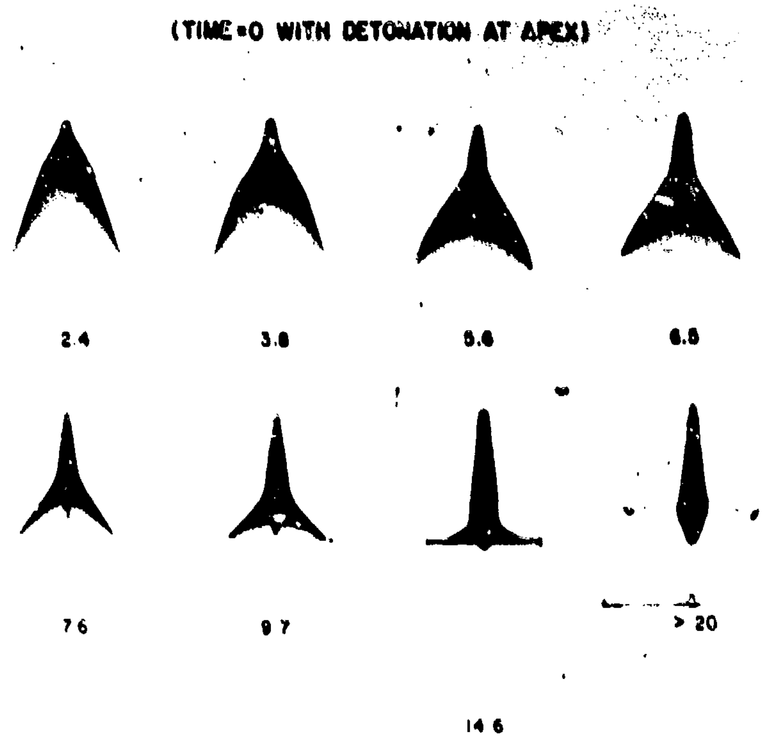

FIG.5 SHAPED CHARGE LINER COLLAPSE

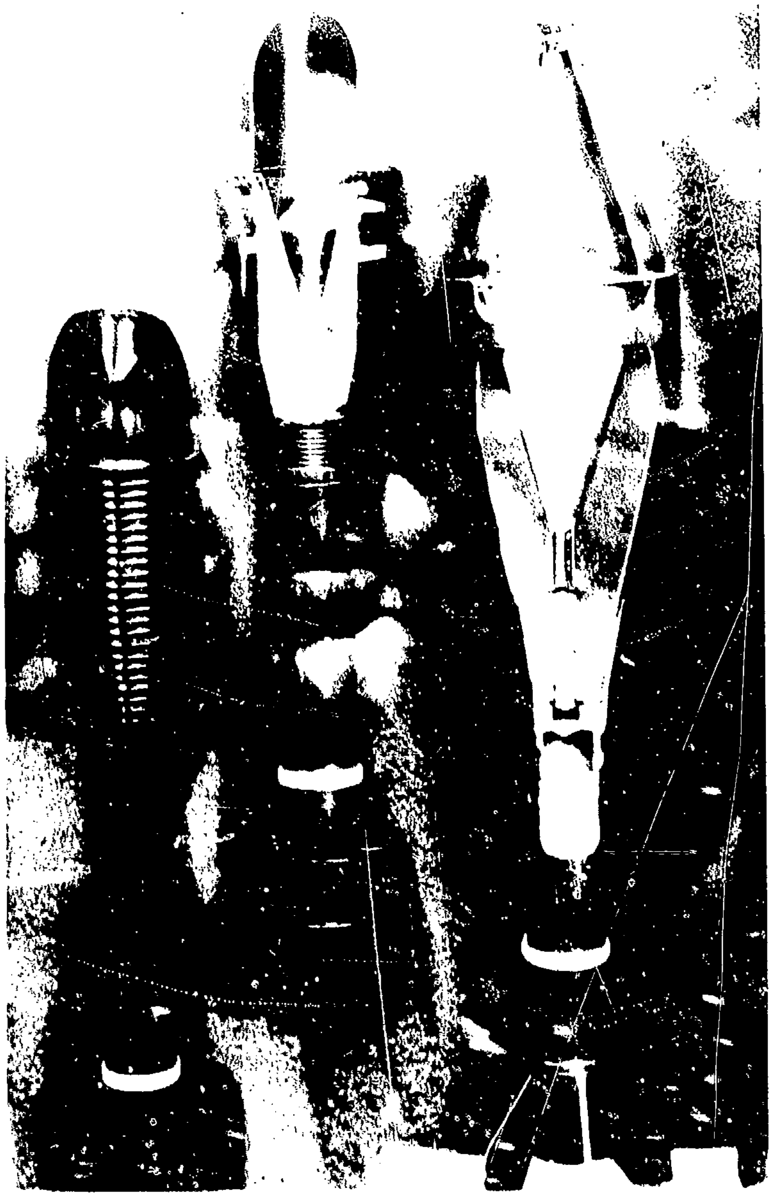

FIG.6 GRENADE NO. 85 MK 1 (CENTRE)

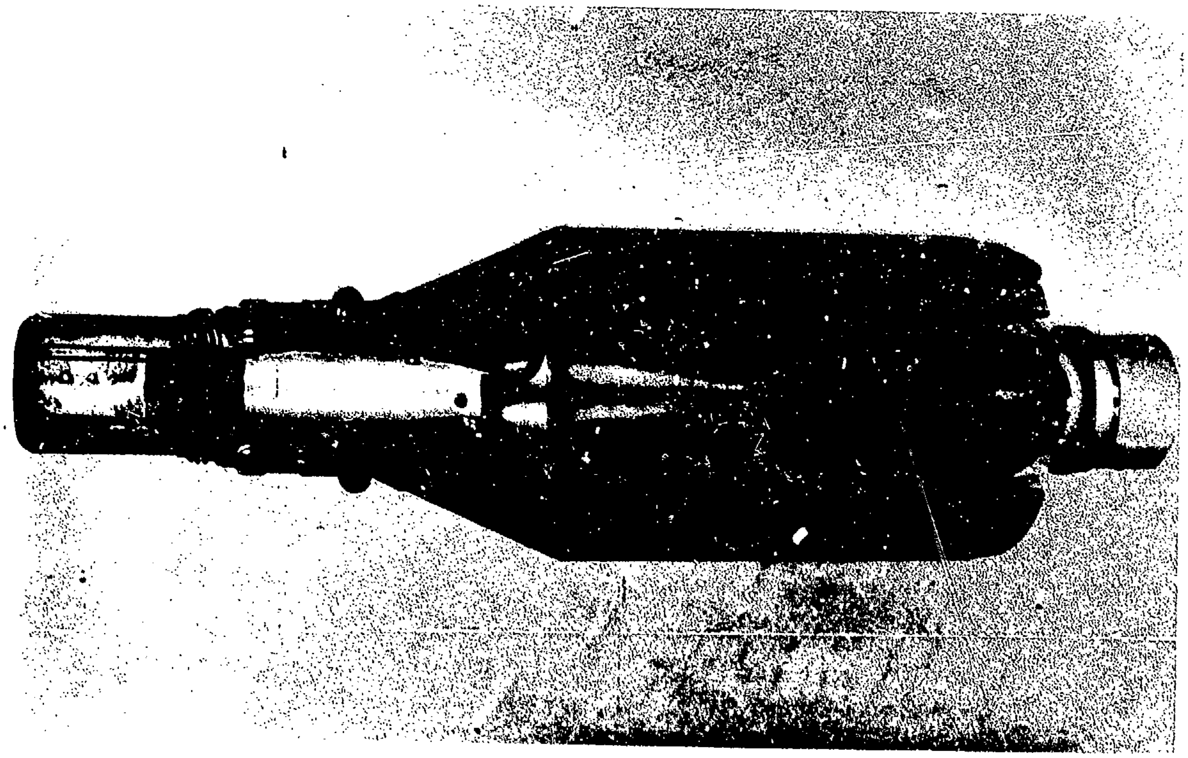

FIG.7 VIGILANT WARHEAD

FIG.8 SWINGFIRE WARHEAD MK 1

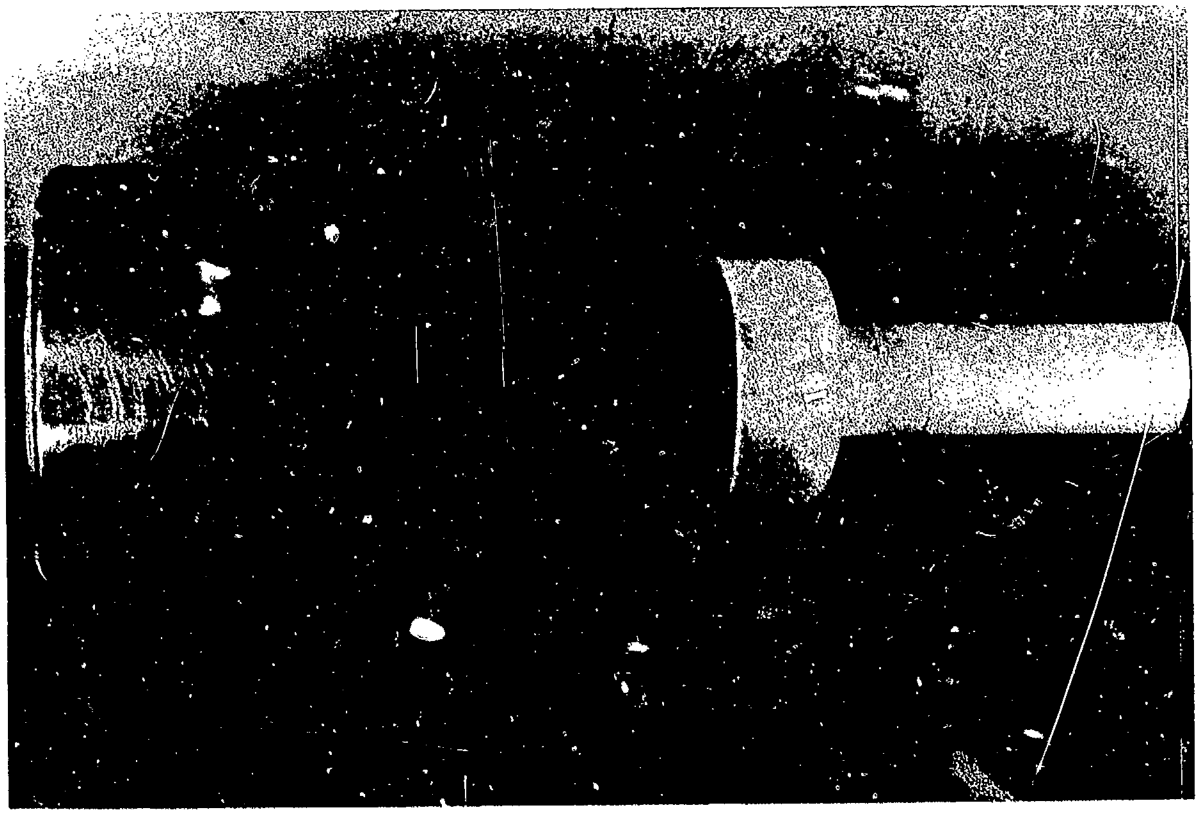

FIG.9 BL755 WARHEAD

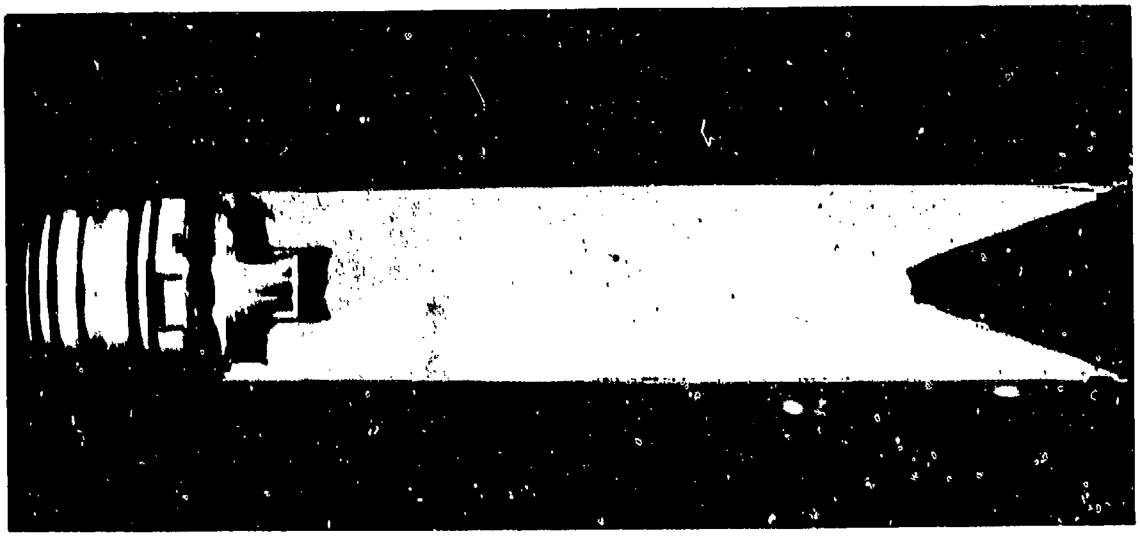

FIG.10 BLOWPIPE WARHEAD

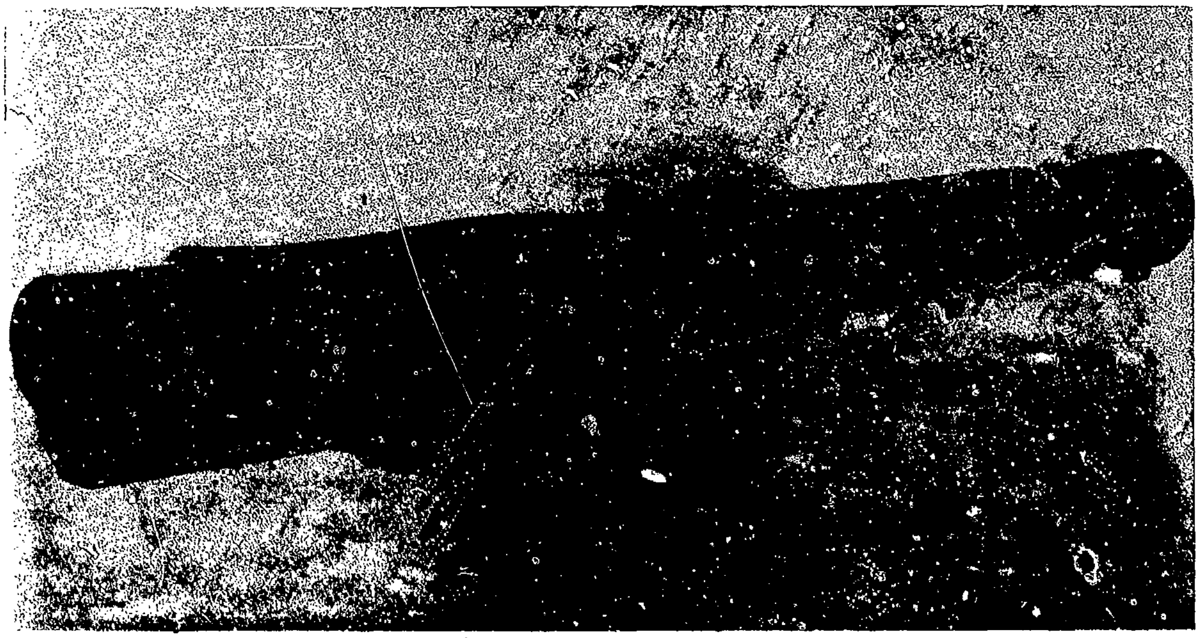

FIG.11 LAW 80

FIG.12 JP 233

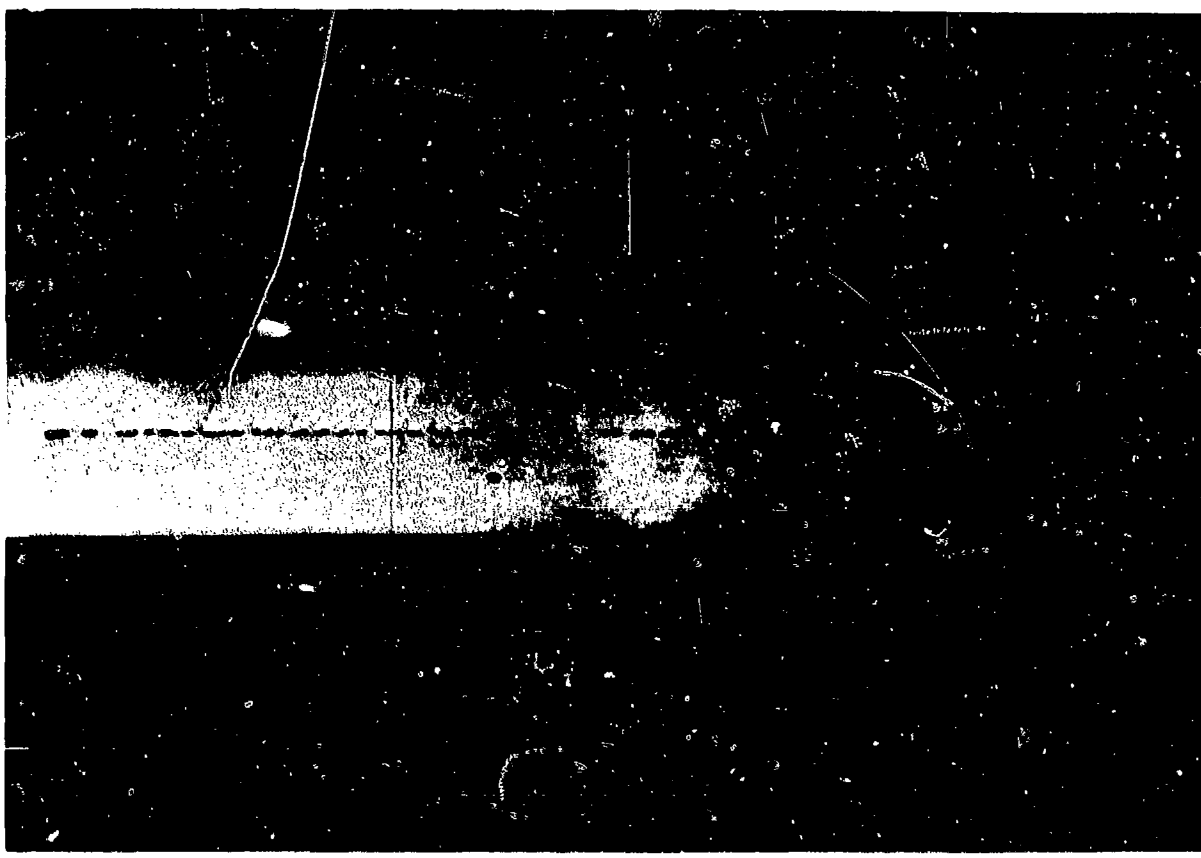

FIG.13 JET FROM MODERN SHAPED CHARGE WARHEAD

REPORT DOCUMENTATION PAGE

(Notes on completion overleaf)

Overall security classification of sheet ......UNLIMITED......

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Abstract

A short account is given of shaped charge development, starting in Norway in the 18th century, noting the first patent applications and then concentrating upon UK developments during World War II and the following years.

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